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Calibration and Performance Evaluation of a Single-Wavelength Transmissometer for Monitoring Particulate Mass Concentration of Emissions from Stationary Sources

SRI International, Menlo Park, CA

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CALIBRATION AND PERFORMANCE EVALUATION OF A SINGLE-WAVELENGTH TRANSMISSOMETER FOR MONITORING PARTICULATE MASS CONCENTRATION OF EMISSIONS FROM STATIONARY SOURCES

Final Report

July 1978

By: Edward E. Uthe, Senior Atmospheric Physicist

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U.S. Environmental Protection Agency
Division of Stationary Source Enforcement
401 M Street, N.W.
Washington, D.C. 20460
and
U.S. Environmental Protection Agency
National Enforcement Investigation Center
Post Office Box 25227
Denver, Colorado 80225

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SRI International
333 Ravenswood Avenue
Menlo Park, California 94025
(415) 326-6200
Cable: SRI INTL MNI
TWX: 910-373-1246

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COLOR ILLUSTRATIONS REPRODUCED IN BLACK AND WHITE

By: Edward E. Uthe, Senior Atmospheric Physicist

Prepared for:

U.S. Environmental Protection Agency
Division of Stationary Source Enforcement
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Washington, D.C. 20460
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Post Office Box 25227
Denver, Colorado 80225

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Approved:

R.T.H. Collis, Director
Atmospheric Sciences Laboratory

Earle D. Jones, Executive Director
Advanced Development Division

SRI International

ABSTRACT

This experimental study investigated the validity of using a single-wavelength infrared transmissometer to measure mass concentration of particulate emissions from stationary sources. Previous data and theory have indicated that an optimum wavelength region (3 to 4 μm) exists for relating aerosol extinction to mass concentration, independent of size of the scattering particles.

A relatively simple and inexpensive 3.39-μm wavelength transmissometer was constructed using a HeNe laser and a pyroelectric detector. The infrared transmissometer was mounted parallel to a white-light transmissometer installed across an aerosol chamber facility. Two-wavelength transmission measurements were made using generated aerosols of known particulate concentration, size, and composition. The aerosols included four size fractions of fly ash, three size fractions of silica, and a single fraction of iron oxide.

Results show that the extinction-to-mass concentration ratio for a given aerosol type is dependent on particle size at the visible wavelength but nearly independent of particle size at the infrared wavelength. Therefore, the infrared transmissometer is an eminently suitable instrument for monitoring mass concentration of particulate emissions with uncontrolled particle sizes. Moreover, the results obtained for the different particle types indicate that this transmissometer can provide estimates of particulate volume concentration that are nearly independent of particle shape, composition, or size.

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I INTRODUCTION AND SUMMARY

Particulate emissions from stationary sources are regulated by visible emission (opacity) and particulate mass concentration standards. Available white-light in-stack transmissometers are a reliable and relatively inexpensive means for monitoring opacity. The opacity-to-mass concentration relationship is strongly dependent on the size distribution of the scattering particles; therefore, opacity readings can be calibrated to provide reliable mass concentration readings only for sources where the particle size distribution is relatively constant. No similarly acceptable technique using transmissometry is currently available for monitoring mass concentration of particulate emissions.

Theoretical and experimental results for fly-ash aerosols show that the white-light extinction-to-mass concentration ratio decreases with increasing particle size (Uthe and Lapple, 1972). Theoretical consideration of infrared wavelengths indicates that the extinction-to-mass concentration ratio (σ/M) generally becomes smaller with increasing wavelength. The greatest decrease occurs for smaller particle sizes. At a wavelength of 10 μm, the dependence of σ/M on particle size is just reversed from that in the visible region; σ/M increases with increasing particle size. This implies the existence of a wavelength region where the extinction-to-mass concentration ratio is nearly independent of particle size. Therefore, a transmission (extinction) measurement in this wavelength region would be a good indicator of mass concentration for sources with uncontrolled or variable particle size emissions.

The objective of this study was to evaluate experimentally a single-wavelength infrared transmissometer for measurement of the mass concentra-

tion of particulate emissions from stationary sources.

To achieve this objective economically, an existing facility was used to generate aerosols of known particle size distribution and mass concentration. The facility included a particle feeder and dispersal system, a 10-m long by 50-cm square aerosol tunnel, and a white-light transmissometer. Transmissometer readings provide values of both opacity and mass concentration, using calibration data between mass concentration and extinction coefficient derived for each particulate fraction used in the experiment.

A relatively simple infrared transmissometer--consisting of a HeNe laser with an emission wavelength of 3.39 μm, a pyroelectric detector, and processing electronics--was installed across the aerosol chamber parallel to the white light transmissometer. The outputs of the two transmissometers were plotted on a two-channel chart recorder. Aerosols were generated at two or three concentration levels for each of four size fractions (0 to 10 μm in diameter) of fly ash, one of iron oxide, and three of silica.

The chart readings show that the infrared transmission is substantially larger than the visible transmission for the small-sized fly-ash particulate fractions (for example, 64 percent infrared to 40 percent visible), while the visible transmission is greater for larger-sized fractions (63 percent infrared to 71 percent visible). Equivalent transmission values were observed for aerosols consisting of particles with a broad size distribution. Extinction-to-mass concentration ratios (σ/M) evaluated from the chart readings agree well with computed values using spherical particle scattering theory that formed the basis of this experimental program. At the visible wavelengths, the σ/M values observed for fly ash aerosols with four different particle size distributions varied within a

factor of 4.4 and at the infrared within a factor of 1.6. For the silica aerosols, visible σ/M values again decreased with increasing particle size (a factor of 2.8), while at the infrared wavelength they are nearly independent of particle size (a factor of 1.2). The σ/M values for the iron oxide were two to three times smaller because of the greater mass density of the particulate material. Therefore, in principle, the single-wavelength infrared transmissometer is an eminently suitable means of monitoring mass concentration of particulate emissions from stationary sources with uncontrolled or variable particle sizes, but where the composition remains constant. A plot of the volume concentration-to-extinction coefficient ratio as a function of particle size (Sauter diameter) shows that the infrared transmission is a good indicator of aerosol volume concentration, regardless of particle type or size. The types of particles observed were of different shapes and probably of different absorption coefficients.

On the basis of the experimental results obtained, SRI strongly recommends that a prototype transmissometer similar in design to the laboratory model used in this study be constructed and evaluated on real emission sources. Supporting opacity, mass concentration, and size distribution data should be collected during the field evaluation of the infrared transmissometer.

A second recommendation is to proceed with the development of an appropriate laser radar system for remote monitoring of the mass-concentration of particulate emissions from stationary sources. Data and theory indicate that a three-wavelength system (visible or near infrared, 3 to 4 μm and 10.6 μm) may provide the optimum information on particle size and aerosol mass concentration.

II BACKGROUND

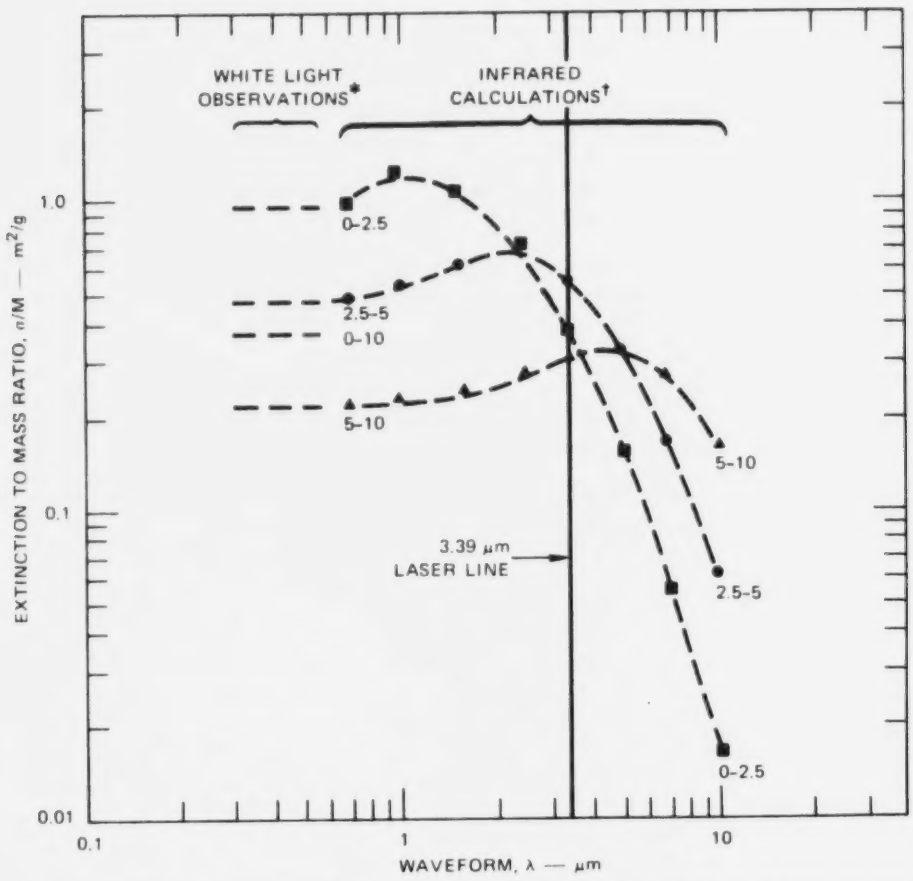
In a previous experimental study (Uthe and Lapple, 1972; Lapple and Uthe, 1976), an aerosol facility was developed for the purpose of investigating relationships between aerosol optical and physical properties and backscatter observations made with laser radar (lidar) systems located at remote distances. The facility provided the means to generate aerosols of known particle size, shape, and composition distributions at various concentration levels within a 10-m long by 50-cm square tunnel with open ends that facilitate laser experiments. During the previous study, raw fly-ash particulates were processed into four fractions, each with a different particle-size distribution; the particulate material was then used to generate aerosols that were observed by white-light transmissometer and quasi-monochromatic visible (0.7-μm) and near-infrared (1.06-μm) lidar systems. Extinction-to-mass concentration ratios were measured at the wavelengths of the three optical instruments for fly-ash aerosols generated with the four size fractions. In addition, spherical particle scattering theory was used with measured particle-size distributions to compute optical parameters (backscatter and extinction coefficients) for comparison with experimental values. For the three optical instruments, both experimental and theoretical values showed that backcatter- and extinction-to-mass concentration ratios decrease with increasing of particle size. However, the rate of decrease of the backscatter-to-mass concentration ratio with respect to particle size was less at the 1.06-μm wavelength than at 0.7 μm. Therefore, lidar backscatter measurements at 1.06 μm are a better indicator of aerosol mass concentration when the particle size distribution is uncertain.

The consideration of the extinction-to-mass concentration ratios can be

extended to longer infrared wavelengths using scattering theory and particle size distributions. The size distribution of each fly-ash fraction was measured and used to obtain the best-fit log-normal distribution function (see Uthe and Lapple, 1972 for details). Figure 1 presents computational results for the extinction-to-mass concentration ratio (σ/M) as a function of wavelength for three fly-ash particulate size fractions. Also shown in Figure 1 are the experimentally determined white-light σ/M values which are in good agreement with σ/M values computed at 0.7 μm.

The data presented in Figure 1 shows that σ/M generally becomes smaller at longer wavelengths; the greatest decrease occurs with the smaller size fractions. At a wavelengh of 10 μm, the dependence of σ/M on particle size is just reversed from that in the visible wavelength region, with σ/M increasing with increasing particle size. It is evident that a wavelength region exists where σ/M is relatively insensitive to variations in particle size and a transmission measurement in this wavelength region would be a good indicator of mass concentration, regardless of particle size. However, the computations presented in Figure 1 assumed that the particulate refractive index was invariant over the wavelength region and that the scattering particles were spherical shaped and nonabsorbing. Because the absorption coefficient of fly ash in the infrared is not well known and because a full theory for irregular shaped particles is not available, the mass measuring transmissometer is more readily evaluated experimentally than theoretically.

The objective of this study was to demonstrate experimentally that a relatively simple and inexpensive single-wavelength infrared transmissometer is an effective means of monitoring particulate mass concentrations of stationary



*Values measured by Uthe and Lapple for fly ash aerosols with 0–2.5, 2.5–5 amd 5–10 μm diameter size fractions.

†Based on log normal size distributions fitted to measured fly ash size distributions.

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FIGURE 1 THEORETICAL DEPENDENCE OF THE EXTINCTION-TO-MASS RATIO OF FLY ASH AEROSOLS ON PARTICLE SIZE AND WAVELENGTH OF THE LIGHT SOURCE

source emissions with uncontrolled particle-size distributions.

III EXPERIMENTAL FACILITY

A. *Aerosol Generating Facility*

Details of the aerosol generating and tunnel system have been discussed by Uthe and Lapple (1972). Under another program, the aerosol tunnel has recently been reconditioned and moved to a new location better suited for use with remotely located laser radar systems. The present tunnel system is shown in Figure 2. Optical tables were constructed at each end of the tunnel to provide platforms that facilitated transmissometer installation and stabilized transmissometer alignment during tunnel operations.

Particulate material was metered out by a proprietary grooved-disk feeder; feed rate was controlled by disk rotational speed. The material was exhausted pneumatically from the groove and dispersed via a sonic-velocity stream into air flow provided by a centrifugal blower. Total air flow was measured as 5800 ft^3/min. Dust-laden air was gradually decelerated in an expanding ductwork and allowed to enter a plenum chamber beneath the aerosol sighting tunnel. Two nozzles located at the chamber ends generated aerosol-laden air curtains to carry away any outside air blown into the tunnel and thus establish a fixed boundary to the dust-laden air in the sighting tunnel. An array of 55 1.25-inch holes in the center of the chamber provided passage of dust-laden air into the tunnel, hence toward the aerosol curtains and out the exhaust stacks. Further details of design and operation of the system are provided by Lapple and Uthe (1976) and Uthe and Lapple (1972).

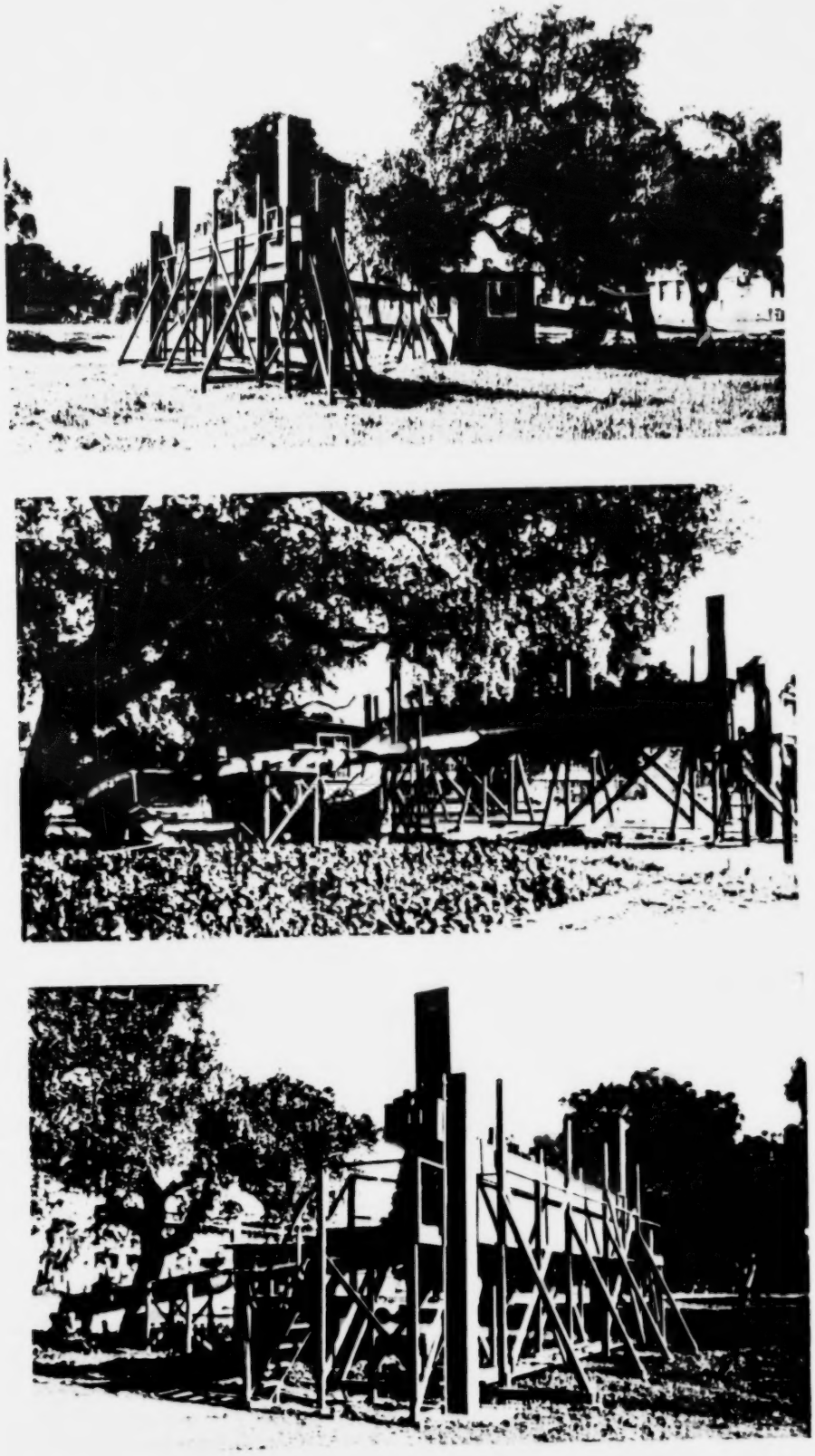


FIGURE 2 VIEW OF AEROSOL CHAMBER WITH CONCRETE COLUMNS TO SUPPORT TRANSMISSOMETER OPTICS

B. *Particulates*

Fly-ash particulate material in four different size fractions was available in limited quantities from the earlier study. Details of the fly-ash preparation and properties have been discussed by Uthe and Lapple (1972). Figure 3 presents scanning electron micrographs of each fraction that shows that most of the particles are spherical in shape. Particle-size distribution measurements have been reported upon in the earlier study.

In addition to the fly ash, iron oxide and three size fractions of silica* particulate material were also available. A detailed study of the properties of these particulates has not been made; however, micrographs are shown in Figure 4 and results of Fisher analysis (Sauter diameter) are given in Table 1.

C. *Transmissometers*

Independent infrared and visible transmissometer systems were used to make extinction measurements of generated aerosols. The white-light transmissometer system was available from the earlier backscatter study and transmissometer output was previously calibrated in terms of mass concentration for aerosols generated from each fly ash fraction by the expression:

$$I = I_o \exp -\{(\sigma/M)\ M\ L\},$$

where I_o is the transmissometer output for a "clear" tunnel, M is the aerosol mass concentration, L is the path length through aerosol laden air (10 m) and σ/M is the extinction-to-mass concentration ratio determined for each particu-

*Min-U-Sil available from Pennsylvania Glass Sand Co., Pittsburgh, Pa.

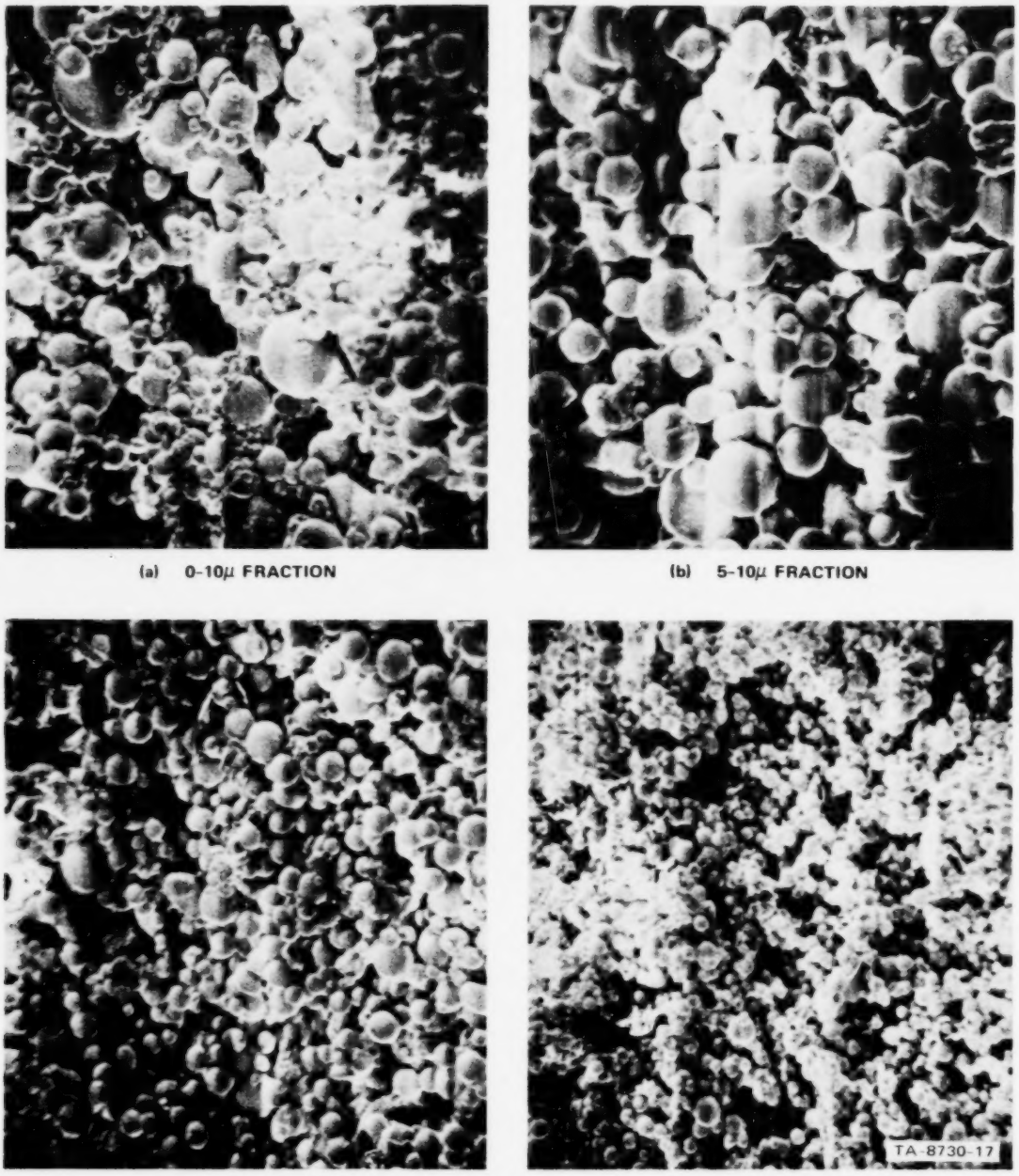


FIGURE 3 SCANNING ELECTRON MICROGRAPHS OF BLACKDOG FLY ASH

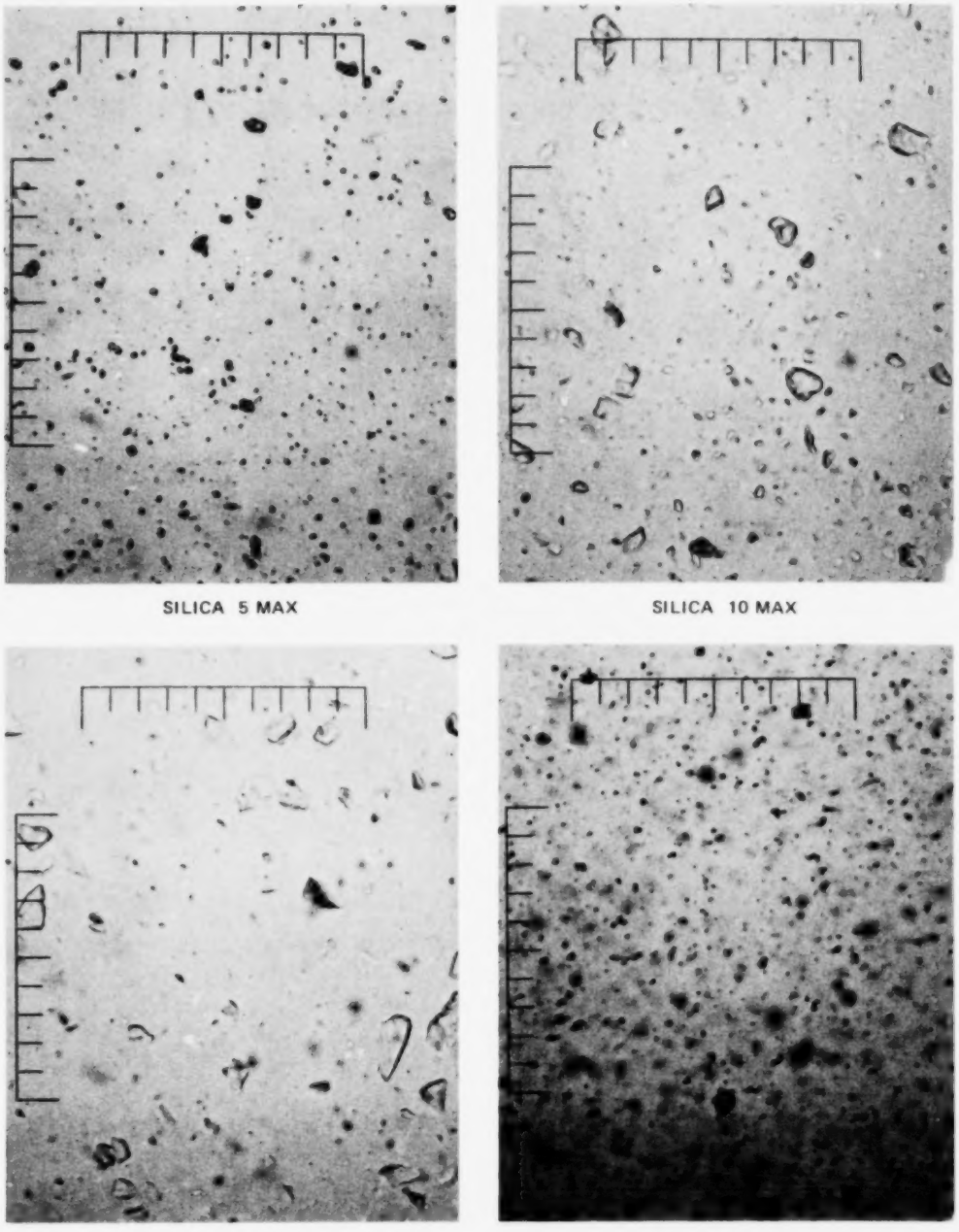


FIGURE 4 MICROGRAPHS OF SILICA (MIN-U-SIL) AND IRON OXIDE PARTICULATE FRACTIONS

Table 1

PARTICULATE PROPERTIES

Particulate		Specific Gravity	Fisher Analysis Sauter Diameter (μm)
Type	Size Indicator (μm)		
Fly ash	0-2.5	2.46*	1.7
Fly ash	2.5-5	2.46*	3.1
Fly ash	5-10	2.46*	6.5
Fly ash	0-10	2.46*	4.0
Iron oxide		4.2	1.25
Silica	5 max	2.65	0.88
Silica	10 max	2.65	1.43
Silica	15 max	2.65	2.09

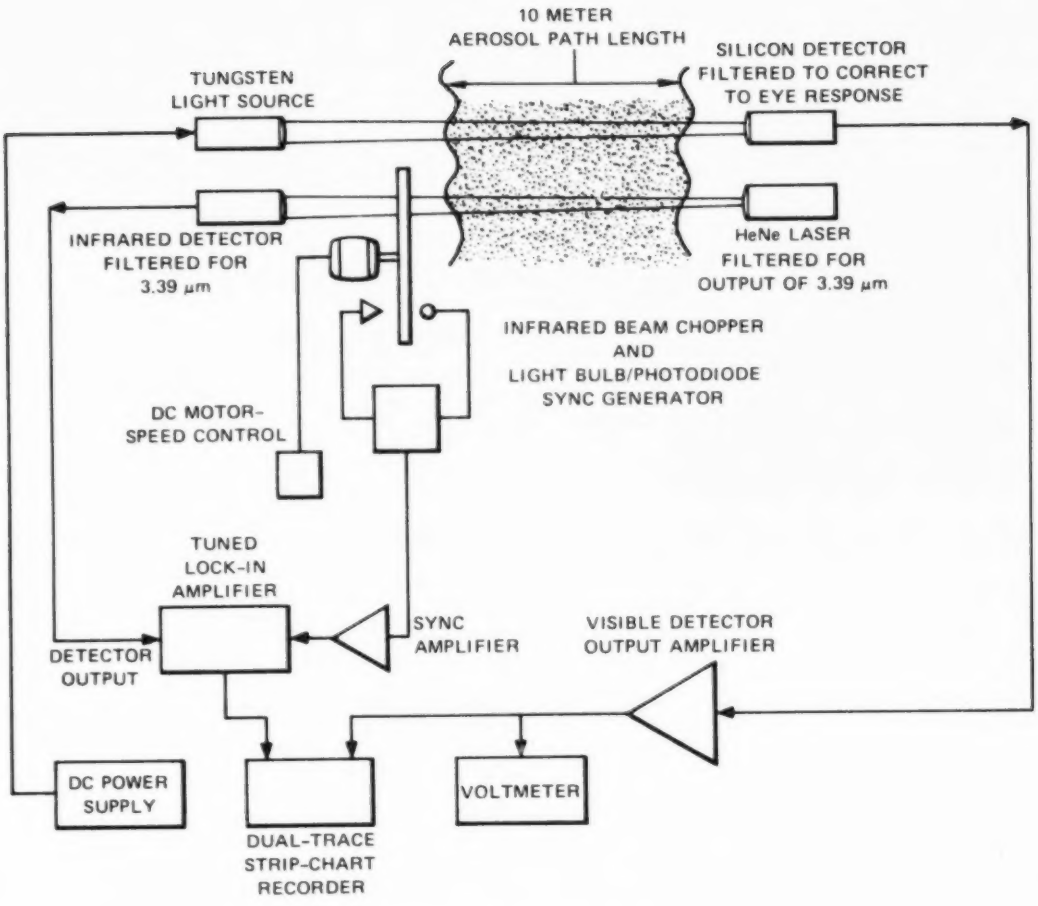
*Determined experimentally for one fraction

(Lapple and Uthe, 1976)

late fraction by independent transmission and mass-concentration measurements. For this study, transmission measurements ($T=I/I_o$) were used with previously evaluated σ/M values to evaluate mass concentrations of generated fly ash aerosols. Values of σ/M for the iron oxide and silica particulates were experimentally evaluated by making independent particle feed-rate measurements.

An infrared transmissometer was designed and constructed using a HeNe laser, pyroelectric detector, and lock-in amplifier that were available at SRI. Infrared (3.39-μm) laser optics and a telescope system were purchased to facilitate construction using available components. The transmissometer systems were installed on optical rails attached to tables located at each viewing end of the aerosol tunnel. A block diagram of the transmissometer systems is shown in Figure 5; photographs of the unit appear as in Figure 6. Visible and infrared transmissometer outputs were plotted on a two-channel chart recorder, which was run continuously during aerosol generating periods. In addition, the output of a microwitch, which was triggered once for each rotation of the particle feeder disk, was connected parallel to the visible transmissometer channel. Resulting marks on the chart recorder provide a measure of disk rotation speed for evaluating particulate mass flow through the system. The chart readings provided both permanent data records and real-time data display required for adjusting light levels and evaluating transmissometer performance before and after each experimental run.

A set of infrared neutral-density filters was not available; hence, typical calibration procedures could not be followed. Rather, the linearity of the instrument was checked by evaluating extinction-to-mass concentration ratios for



TRANSMISSOMETER CHARACTERISTICS

INFRARED

- TRANSMITTER

  BEAM DIAMETER AT SOURCE: 1.88 mm
  BEAM DIVERGENCE: 2.3 mrad
  BEAM WAVELENGTH: 3.39 μm
  BEAM ENERGY: 1.2 mW AT 3.39 μm
  BEAM SPOT SIZE AT 10 m: 2.3 cm (3-dB POINTS)

- RECEIVER

  3.8-cm DIAMETER TELESCOPE
  FIELD OF VIEW: 16.7 mrad (5 mm ACTIVE DETECTOR AREA)

VISIBLE

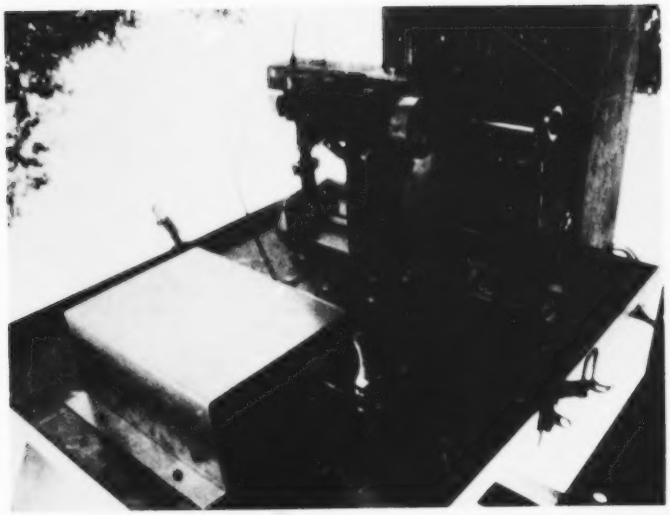
- TRANSMITTER

  1.8 -INCH DIAMETER LIGHT SOURCE FOCUSED AT 32 FEET (PATH LENGTH)
  FOR SPOT SIZE OF 1.5 -INCH DIAMETER

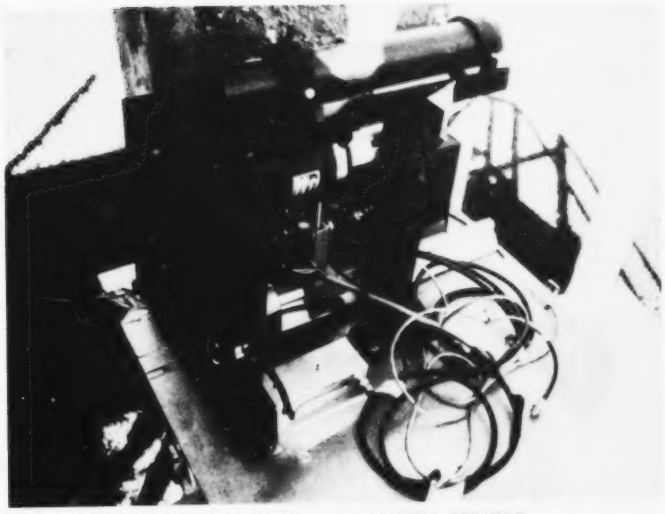
- RECEIVER

  FOCUSED AT 32 FEET WITH 3.3 -INCH DIAMETER FIELD OF VIEW

FIGURE 5 BLOCK DIAGRAM OF TRANSMISSOMETER SYSTEMS



(a) IR SOURCE AND VISIBLE DETECTOR



(b) IR DETECTOR AND VISIBLE SOURCE

FIGURE 6 VIEWS OF TRANSMISSOMETER SOURCES AND DETECTORS

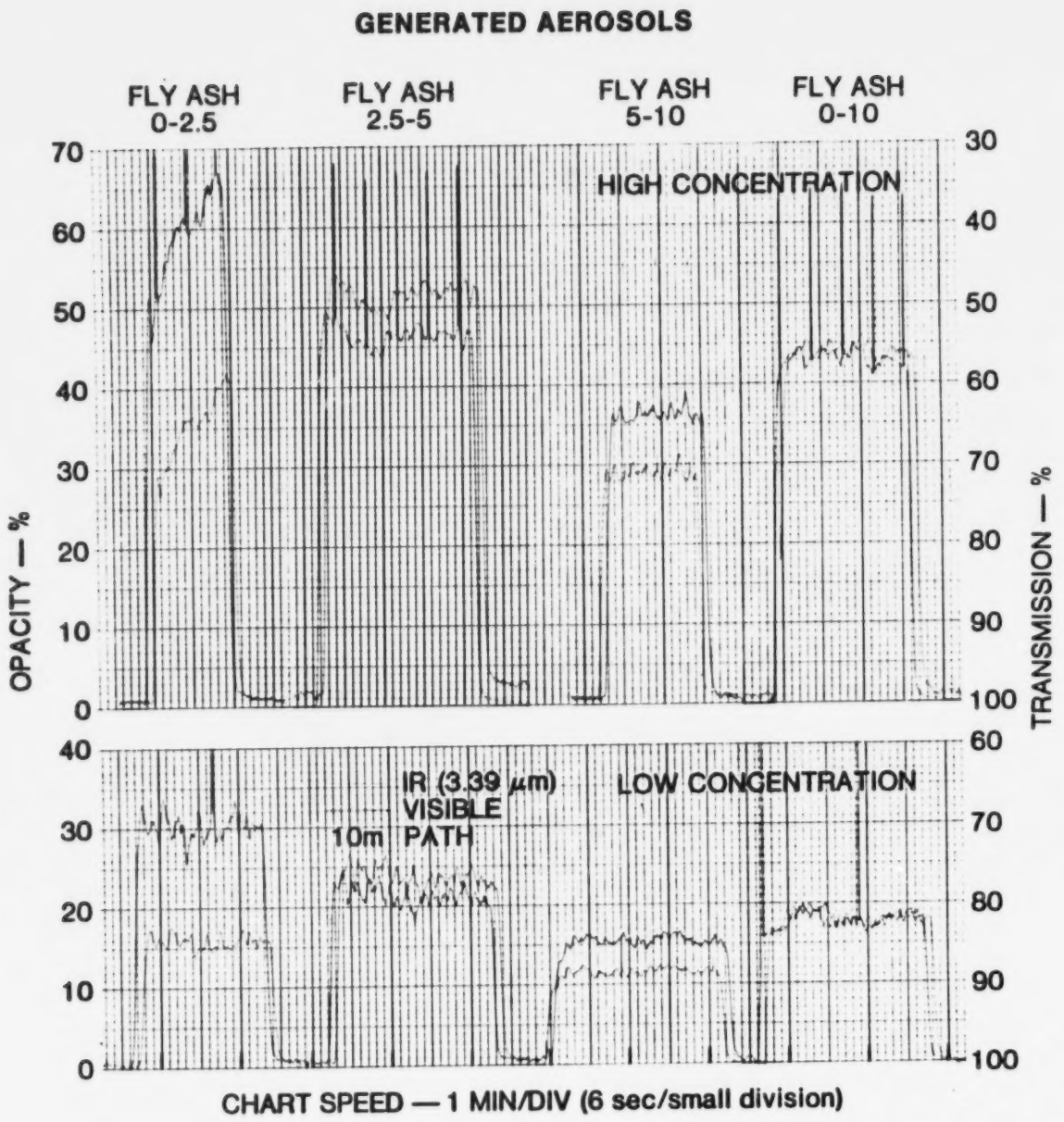
several particulate feed rates, which should be constant for a linear response transmissometer. Because the optical components used in the transmissometer are expected to be linear over the range of operating conditions used, the transmissometer was always adjuted for 0- and 100-percent values and the aerosol linearity checks were typically within 4 percent, the transmissometer was judged to be sufficiently linear for the observation program discussed below.

IV EXPERIMENTAL DATA AND RESULTS

A major effort of this study was the design, construction, installation, and testing of the infrared transmissometer system.

Once satisfactory performance had been achieved (as determined by obtaining consistent extinction-to-mass concentration ratios at different particulate feed ratios--see discussion above), the data-collection effort was completed within a few days. The experimental procedure consisted of loading the particle feeder with particulate material, adjusting transmissometer light levels and detector sensitivities for a 0-100 percent full-scale reading on the chart recorder, and generating aerosols for approximately a one- to two-minute period at each of several aerosol mass concentration levels.

Examples of transmissometer traces (edited to eliminate 0 and 100 percent calibrations) recorded during fly-ash data runs are presented in Figure 7. The data include both infrared and visible transmissometer traces for fly-ash aerosols of four different size distributions generated at two different concentration levels (the mass concentration at each level, however, varies from fraction-to-fraction). The infrared transmissometer trace (red) lags the visible trace (blue) by one small division (6 s). Small-scale aerosol concentration variations within the aerosol tunnel causes similar small-scale variability on both traces, indicating that the transmissometers were observing similar concentration levels. The data presented in Figure 7 clearly show significant differences between infrared and visible transmission as a function of particle size. For the smallest fraction (0 to 2.5 μm), a visible transmission of 40 percent corresponds to an infrared transmission of about 64 percent. For the 0- to 2.5-



Infrared trace lags visible trace by one small division

FIGURE 7 EXAMPLES OF TWO-WAVELENGTH TRANSMISSOMETER TRACES FOR GENERATED FLY-ASH AEROSOLS

μm fraction, the infrared transmission is less (48 percent to 59 percent for visible). This difference is approximately the same as for the 5- to 10-μm fraction. As expected, the broad 0- to 10-μm fraction gives nearly equivalent transmissions in the visible and infrared.

Visible and infrared transmission values were read from the chart records using the 0- and 100-percent calibration data collected before each data run. Visible transmission values were used with the previously evaluated extinction-to-mass concentration ratios $(\sigma/M)_V$ to estimate aerosol mass concentration within the tunnel by the expression $M = -\ln T_V/L(\sigma/M)_V$, where L = chamber length. The infrared and visible transmission values were used to derive the quantity $(\sigma/M)_I/(\sigma/M)_V = \ln(T_I - T_V)$ and the previously evaluated $(\sigma/M)_V$ values were applied to determine extinction-to-mass ratios at the infrared wavelength. These results are given in Table 2. The extinction-to-mass concentration ratios for a given particulate fraction should be independent of concentration for a linear response transmissometer. The largest difference between the 40 and 100 feed indicators is 4 percent, which is consistent with a linearity of ± 2 percent (see Section III C). Linearity of the visible transmissometer has been checked on previous programs and found to be within $\pm 2\%$.

Infrared σ/M values are nearly equal for the 0- to 2.5-μm and 2.5- to 5-μm fractions, while σ/M values in the visible region differ by a factor of 2. Therefore, the 3.39-μm wavelength transmissometer is an excellent instrument for monitoring mass concentrations of aerosols with size disributions varying between those of these two fractions. Among the four fractions, σ/M values vary by a factor of 4.4 at the visible wavelength, the variability is within a factor of 1.6 at the infrared wavelength. The observed infrared σ/M values are in

Table 2

CHARACTERISTICS OF EXPERIMENTAL

FLY-ASH AEROSOLS

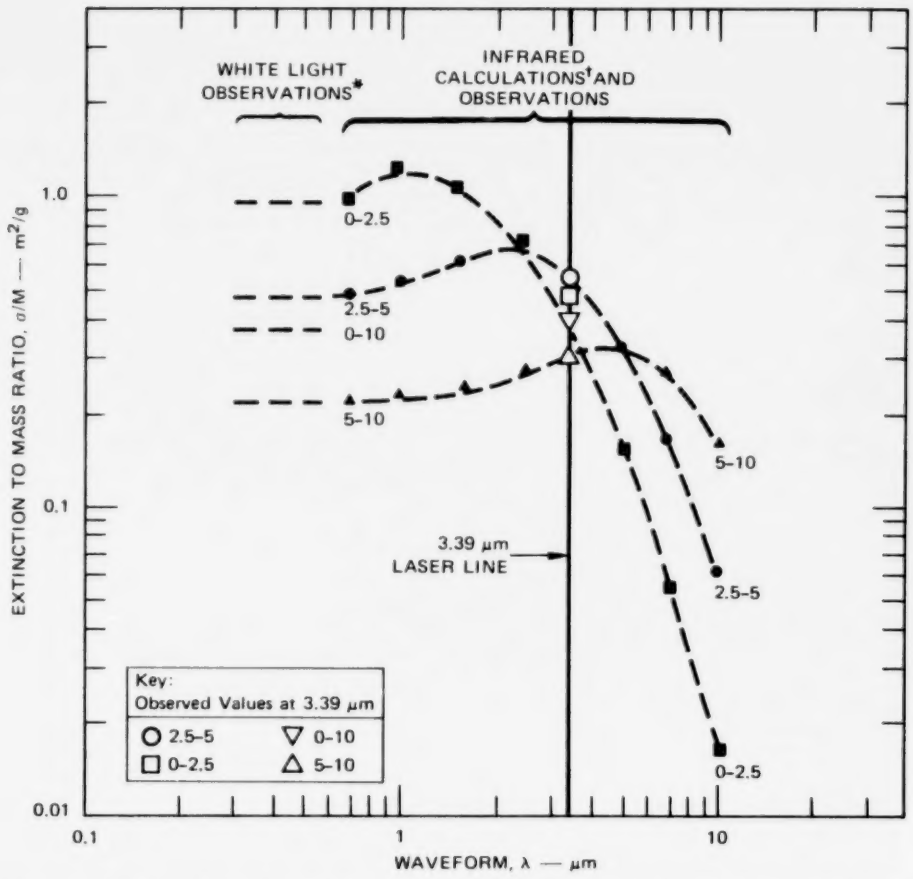
Particle Size Range (μm)	Motor Setting	Instantaneous Transmission, T (%)		Particle Mass, M (mg/m^3)	$\frac{(\sigma/M)_{IR}}{(\sigma/M)_V}$	Extinction to Mass Concentration Ratios, σ/M (m^2/g)	
		Visible	Infrared			Visible	Infrared
0-2.5	40	69.3	84.0	38.9	0.475	0.943	0.448
		71.0	85.1	36.3	0.471	0.943	0.444
0-2.5	100	39.9	64.2	97.4	0.482	0.943	0.455
		38.0	63.2	102.6	0.474	0.943	0.447
2.5-5	40	78.5	75.8	53.8	1.145	0.450	0.515
		77.0	74.7	58.1	1.116	0.450	0.502
		78.0	75.2	55.2	1.147	0.450	0.516
2.5-5	100	54.1	49.6	136.9	1.141	0.450	0.514
		53.1	48.5	140.7	1.143	0.450	0.514
5-10	40	88.5	85.4	57.1	1.292	0.214	0.276
		88.3	84.8	58.1	1.325	0.214	0.284
5-10	100	71.3	63.9	158.1	1.324	0.214	0.283
0-10	40	80.1	80.0	66.0	1.006	0.336	0.338
		81.0	81.1	62.7	0.994	0.336	0.334
0-10	100	55.0	53.9	177.9	1.034	0.336	0.347

good agreement with theoretically computed values, as shown in Figure 8.

In addition to the fly-ash aerosols, two-wavelength transmission observations were made using other aerosols, which were generated with available particulate material. Figure 9 presents transmissometer traces recorded for one size fraction of iron oxide and three size fractions of silica (silicon dioxide). The infrared transmission is signficantly larger than the visible transmission for all fractions, indicating relatively small particle sizes that compare most closely with the 0- to 2.5-μm fly ash fraction. The extinction properties of iron oxide closely relates to the 10-μm maximum silica fraction. The greatest difference between infrared and visible transmissions is for the smaller sized silica (5 μm maximum) and the difference decreases in a uniform fashion for the larger silica fractions, consistent with results obtained using fly ash aerosols.

Data on the white-light extinction-to-mass ratios were not available for the iron oxide and silica fractions. Therefore, infrared and visible σ/M values were determined by independent evaluation of particulate mass flow from the particle feeder as a function of disk rotation rate. (For details see Uthe and Lapple, 1972). The feed rates (g/rev) used with the disk rotation rates evaluated from microswitch data taken from the visible transmissometer trace and the transmission values averaged over the same period can be used to determine σ/M values. The results of this analysis is given in Table 3.

The σ/M values for iron oxide are about a factor of 2 to 3 less than for the 0- to 2.5-μm fly-ash fraction and the 10-μm silica fraction. Since the particle size and extinction meaurements (at a given particulate feed rate) are about the same for the three fractions, the difference is consistent with the greater specific gravity of the iron oxide (4.2 for iron oxide compared to 2.65 for silica



*Values measured by Uthe and Lapple for fly ash aerosols with 0–2.5, 2.5–5 amd 5–10 μm diameter size fractions.

†Based on log normal size distributions fitted to measured fly ash size distributions.

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FIGURE 8 THEORETICAL AND OBSERVED DEPENDENCE OF THE EXTINCTION-TO-MASS RATIO OF FLY ASH AEROSOLS ON PARTICLE SIZE AND WAVELENGTH OF THE LIGHT SOURCE

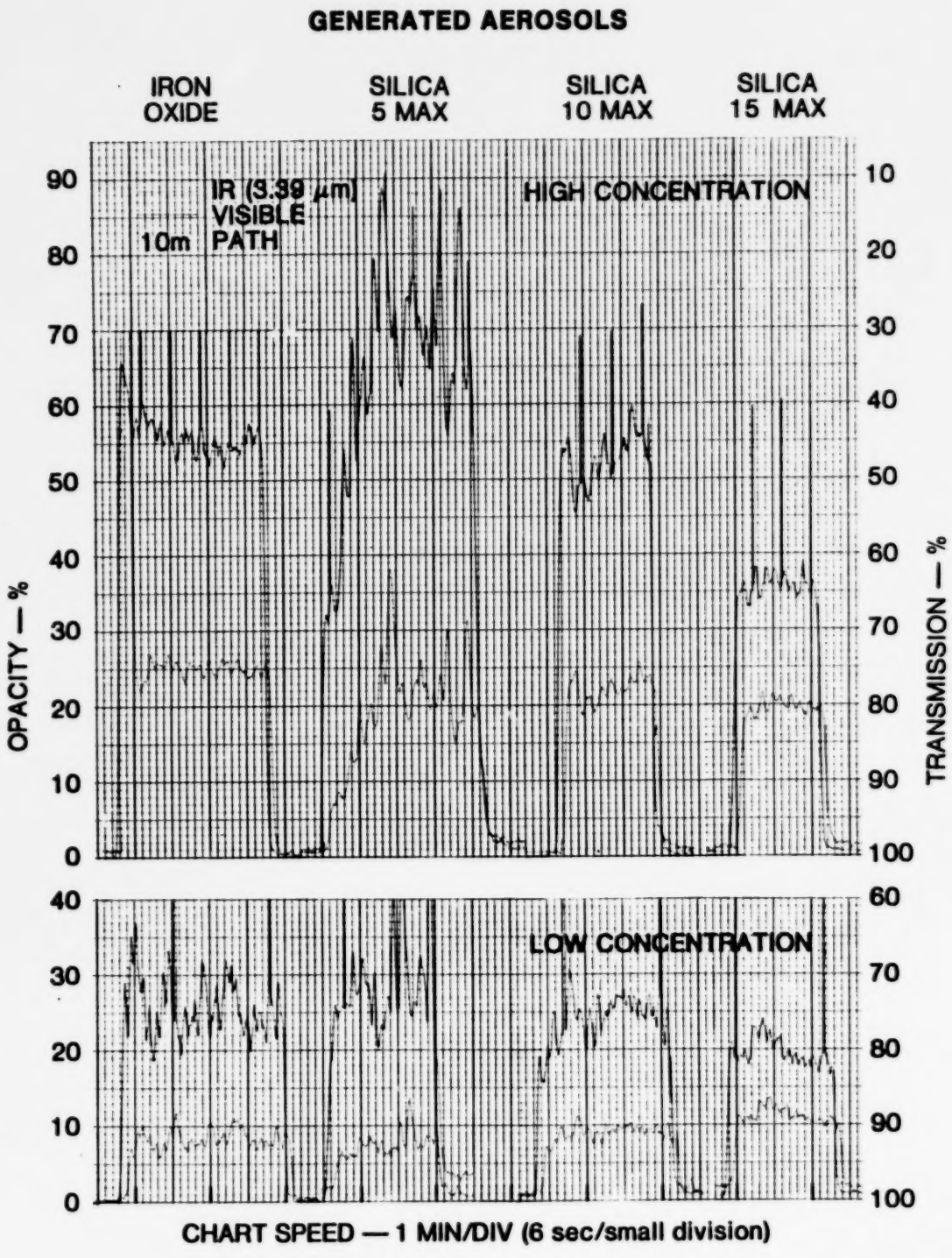

FIGURE 9 EXAMPLES OF TWO-WAVELENGTH TRANSMISSOMETER TRACES FOR GENERATED IRON OXIDE AND SILICA AEROSOLS

Table 3

EXTINCTION AND MASS CONCENTRATION DATA FOR IRON OXIDE AND SILICA AEROSOLS

Material and Particle Size Range (μm)	Motor Setting	Disk Rotational Velocity	Aerosol Mass, Concentration (mg/m^3)	Feed Rate* (g/rev)	Average Transmission T(%)		Extinction Coefficient $\sigma(km^{-1})$		Extinction to Mass Concentration Ratio, $\sigma/\kappa(m^2/g)$	
					Visible Light	IR	Visible	IR	Visible	IR
Iron oxide	40	0.813	61.9	12.5	74.2%	91.5%	29.8	8.88	0.481	0.143
	100	2.61	198.6	12.5	45.3%	75.2%	79.2	28.5	0.399	0.144
Silica 5	40	-	-	7.33	70.2	93.1	35.4	7.15	-	-
max	100	2.78	100.0	5.91	29.7	77.6	121.4	25.4	1.21	0.254
Silica 10	40	0.781	35.3	7.43	75.3	91.5	28.4	8.88	0.805	0.252
max	100	2.47	103.3	6.87	46.5	78.1	76.6	24.7	0.742	0.239
Silica 15	40	0.877	39.8	7.46	80.9	90.0	21.2	10.5	0.533	0.264
max	100	2.83	104.7	6.08	64.0	80.7	44.6	21.4	0.426	0.204

* Particle feeder calibration data determined by weighing collected dust for a large number of disk revolutions.

and 2.46 for fly ash).

The visible σ/M values for silica decrease with increasing particle size (a factor of about 3) while the infrared σ/M values are nearly independent (a factor of 1.2) of particle size (within the experimental accuracy of these observations). Therefore, the infrared transmissometer is an excellent instrument for monitoring the mass concentration of silica aerosols when the particle size varies over the range used in this study.

Figure 10 presents a plot of the extinction-to-volume concentration σ/V ratios (extinction-to-mass concentration ratios weighted by the specific gravity) of the particulate material as a function of the Sauter diameter. The visible wavelength σ/V values clearly show a strong dependence on particle size, while the infrared wavelength values are nearly independent of particle size. Therefore, these data indicate that extinction measurements at 3.39-μm wavelength are a good indicator of particulate volume concentration for the range of materials tested in this study.

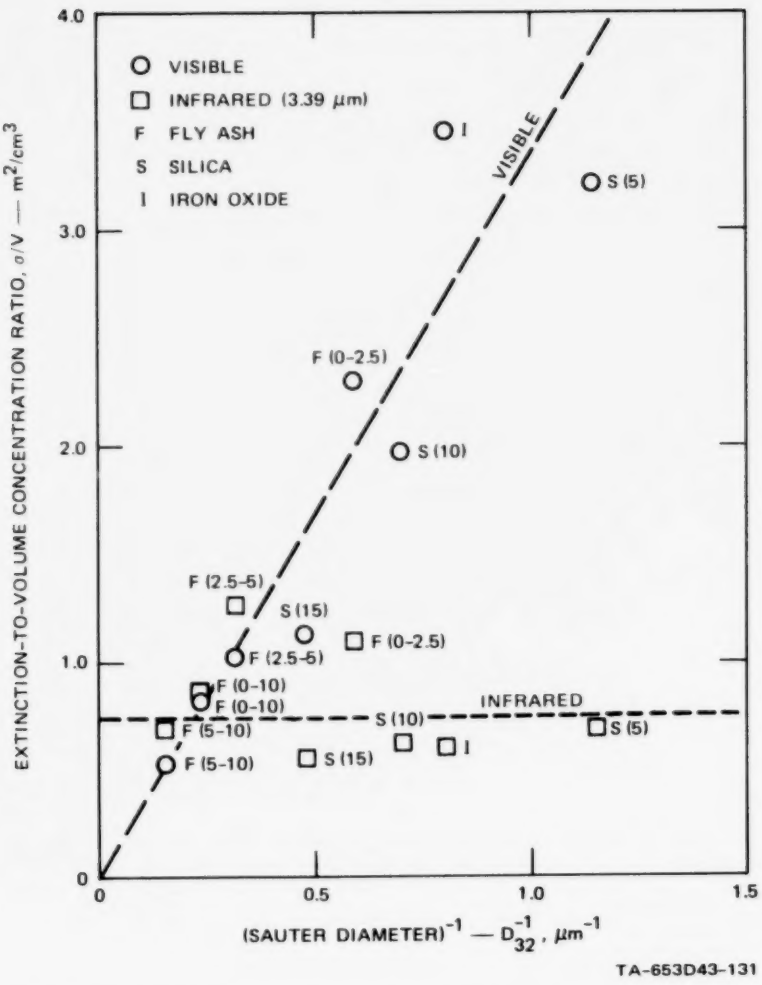

FIGURE 10 EXTINCTION-TO-VOLUME CONCENTRATION RATIOS AS A FUNCTION OF PARTICLE SIZE VISIBLE AND INFRARED (3.39 μm) WAVELENGTHS

V CONCLUSIONS AND RECOMMENDATIONS

A relatively simple and inexpensive single-wavelength infrared transmissometer has been constructed and evaluated as an instrument to monitor the mass concentration of particulate emissions. White-light and infrared transmission measurements were made of generated aerosols of known composition, size, and mass concentrations. For fly-ash aerosols of four different size distributions, in the range of 0- to 10-μm diameter, the infrared extinction-to-mass concentration ratio varied only by a factor of 1.6 while the variability for visible wavelengths was over a factor of 4.4. For silica aerosols of three different (but similar) size disbritutions, the σ/M values at the infrared wavelength were nearly independent of the size fraction observed, while for visible wavelengths the variability was a factor of about 3. Both infrared and visible σ/M values for iron oxide were between 2 and 3 times less than for fly ash or silica because of the greater mass density of the particulate material. Accounting for differences in specific gravity, the extinction-to-volume concentration ratio for all aerosols tested is dependent on the Sauter diameter at the visible wavelength but nearly independent of the diameter at the infrared wavelength. Also, since the particles used in this experiment were of different shapes and compositions, the results indicate that infrared transmission measurements may provide a good measurement of particulate volume concentration for all aerosol pollution sources.

These experimental results agree with theoretical computations, which show that an optimum wavelength region exists for relating light extinction measurements to aerosol mass concentration, independent of particle size effects. This optimum wavelength region for particles used in this study (0- to

10-μm diameter) is near the 3.39-μm wavelength. Therefore, the experimental technique and results of this program provide the basis for accelerating development and application of an instrument for monitoring mass concentration of particulate emissions from stationary sources. However, real sources present problems that were not encountered in this laboratory experiment. For example, interference by gas absorption and high-temperature infrared emission will have to be considered in developing an in-stack instrument. Also, the effect of particulate absorption should be investigated.

Based on the results of this experimental study, SRI highly recommends that a prototype infrared transmissometer similar in design to the laboratory model be constructed and evaluated on real emission sources. Supporting opacity, aerosol mass concentration, and size distribution data should be collected during the field evaluation of the infrared transmissometer.

The transmissometer technique can be extended for remote measurement of aerosol mass concentration. For example, the lidar technique can be used to determine plume transmission by comparing clear-air backscatter from the near and far sides of the plume return. If the measurement is made at an appropriate infrared wavelength, the transmission should be a good indicator of cross-plume mass concentration. In addition, backscatter from the plume particulates at the infrared wavelength may provide a good indicator of mass concentration. Recently, smoke and dust aerosols were observed with lidar systems operating at 0.7- and 10.6-μm wavelengths (Uthe, 1978). The data demonstrated that aerosol type strongly affects wavelength dependence of backscatter and attenuation and were in agreement with the theoretical results presented in Figure 1 of this report. SRI recommends that a 3.8-μm wavelength capability be added to

the 0.7- and 10.6-μm lidar system and that the three-color lidar be used to observe actual particulate emissions from stationary sources. As shown by the data presented in Figure 1, these three wavelengths may provide nearly all the information content on particulate size distribution and mass concentration that can be derived from a multiwavelength remote sensing technique.

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